PERFORMANCE ANALYSIS OF AEROSPIKE ROCKET ENGINES

By

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SUMMARY

The results of an experimental and analytical investigation of the characteristics of the separated flow region for an aerospike nozzle are presented. The primary objective of the investigation was to predict base pressure in the flow recirculation area for open- and closed-wake operation to determine overall engine performance. The developed analytical method and the results of parametric studies including the effects of sonic line shape, internal shock, ambient pressure, base bleed, nozzle area ratio, turbulence effects, plug length, and aerodynamic slipstream are described. A high area ratio, truncated aerospike nozzle as considered by Chrysler Corporation in their single-stage, earth-orbital, reusable vehicle study is discussed, and the performance for various operating conditions is presented.

LIST OF SYMBOLS

Symbol	Definition
A_{ne}	nozzle exit area
A_{nt}	nozzle throat area
C_t	thrust coefficient efficiency
d, j	dividing streamline
L	plug length
L_{max}	ideal plug length
P_{o1}	chamber pressure
P_{amb}	ambient pressure
P_b	base pressure
P_{ne}	nozzle exit pressure
P_{ws}	static-side wall pressure
PR	ratio of ambient and chamber pressure
r	radius normal to nozzle axis
r_3	base radius upstream of recompression shock
r_b	base radius
r_w	trailing wake radius
R, - R	boundary lines separating the mixing free shear layer from the inviscid and base recirculation flow fields
S_L	ordinate of internal shock normal to nozzle centerline
T_{o1}	inviscid flow stagnation temperature
T_b	base flow temperature
u	local velocity in free shear layer
u_a	inviscid flow velocity
x, X	abscissa of coordinate system
y, Y	ordinate of coordinate system
y_m	ordinate of free shear layer
γ	specific heat ratio
ϵ	area ratio

θ	flow angle
$\mathcal{H}$	nondimensional bleed number

INTRODUCTION

In the past, primarily classical rocket engines of the bell type have been used for the propulsion of launch and space vehicles. In the future, advanced rocket propulsion systems will require exhaust nozzles that perform efficiently over a wide range of ambient operating conditions. Furthermore, these exhaust nozzles should be short, lightweight, and relatively easy to cool. Analyses and tests have demonstrated that a group of nozzles referred to as altitude compensating nozzles satisfy these requirements. The expansion-deflection and aerospike nozzles are included in this group (Fig. 1). Altitude compensation in these nozzles is obtained by the flow of the combustion products in the supersonic range. Unlike the bell nozzle, in which the entire flow is contained within a fixed contour, the flow of an aerospike nozzle is guided along the plug only. The outer shroud ends shortly after the nozzle throat and forces the flow to establish its own external contour which must be in pressure balance with the ambient condition. This document will discuss only those aspects relating to the performance analysis of the aerospike nozzle.

AEROSPIKE ENGINE PERFORMANCE

The performance of an aerospike nozzle is composed of two portions; namely, thrust produced by pressure forces acting on (1) the solid wall surfaces guiding the flow and (2) the base area. The latter item primarily will be discussed in this report since it affects performance significantly.

OPEN-CLOSED WAKE OPERATION

Dependent on the chamber-to-ambient-pressure ratio, two significant nozzle operation modes can be identified. At a low pressure ratio, the separated base flow region is open and is sensitive to ambient conditions through the trailing wake corridor. For a high pressure ratio, the base flow field becomes closed preventing any influence of the ambient environment. Experiments have shown that during the open-wake condition the base pressure varies in accordance with the ambient pressure. After the

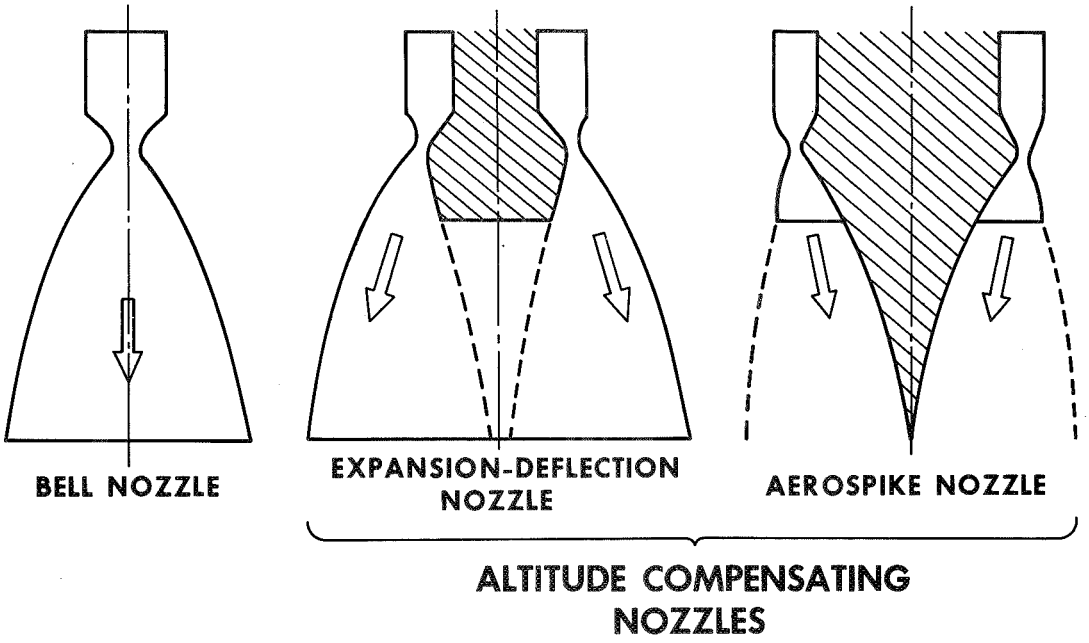


Figure 1. Nozzle types.

wake closes, the base pressure remains constant (Fig. 2).

ANALYTICAL FLOW TREATMENT

The total flow field beginning at the injector can be subdivided into the realms where viscous forces are either negligible or dominant. Viscous effects are insignificant in the core portion of the subsonic, transonic, and supersonic flow fields; whereas strong viscous effects, generated by the interaction of the core flow with the ambient environment and the base recirculation region, must be considered in the boundary layer along the solid surfaces and in the free shear layers (Fig. 3). However, there exist phenomena caused by the boundary and free shear layer which affect the inviscid flow field significantly. Because of the viscous behavior, the boundary layers do not separate from the wall contour at the end of the outer shroud and plug truncation corner, rather they bend around these wall discontinuities and then separate. This effect produces a local overexpansion of the inviscid core flow, represented by an expansion fan. Afterwards, the flow balances itself by changing direction resulting in the generation of internal, lip, and recompression shocks (Fig. 4).

After determination of the chamber and nozzle geometry, the theoretical analysis of the inviscid flow field begins with the calculation of the combustion reaction in the chamber based upon propellant combination, chamber pressure, and mixture ratio. The results are used in a transonic model to generate a sonic start line that, in turn, will be used to calculate the supersonic flow field by the rotational method of characteristics. Solutions of the free jet boundary, internal shock, and recompression shock are included.

The performance of the nozzle down to the plug truncation corner is then determined from the inviscid flow analysis reduced by the losses from the boundary layer. The performance contribution from the base pressure depends upon whether an open- or closed-wake condition exists. For

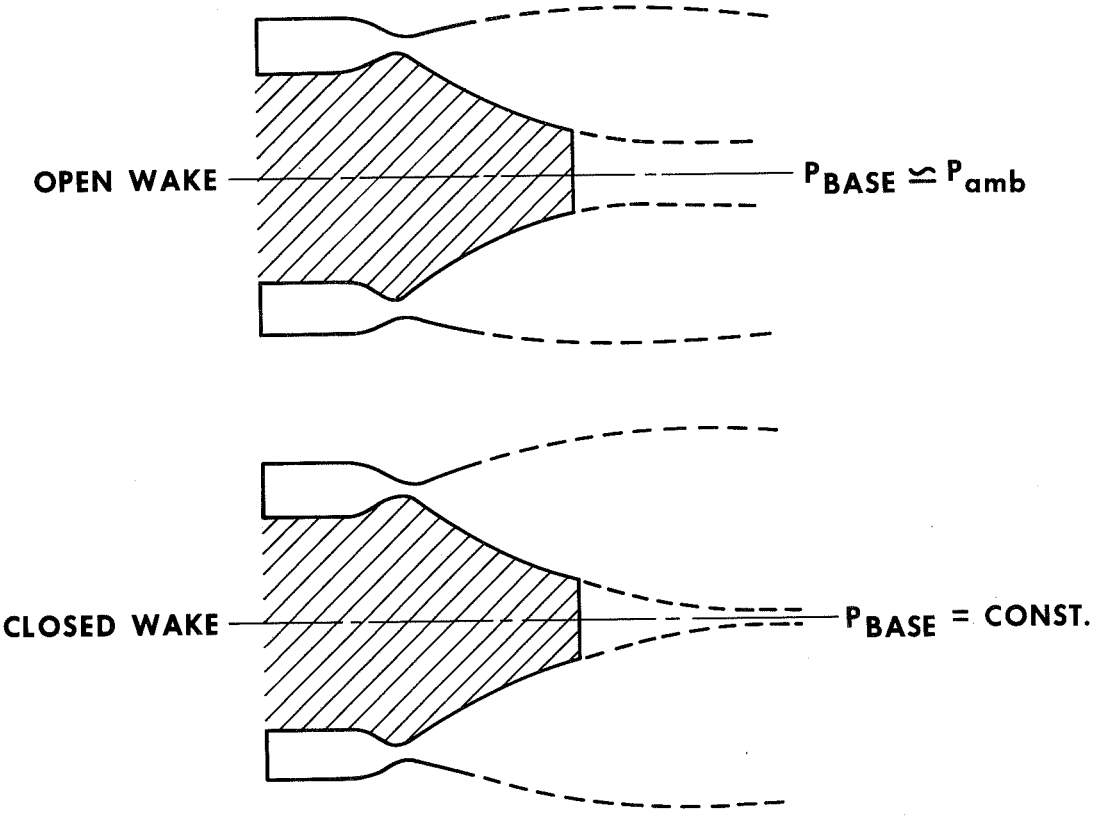


Figure 2. Truncated plug nozzle operation mode.

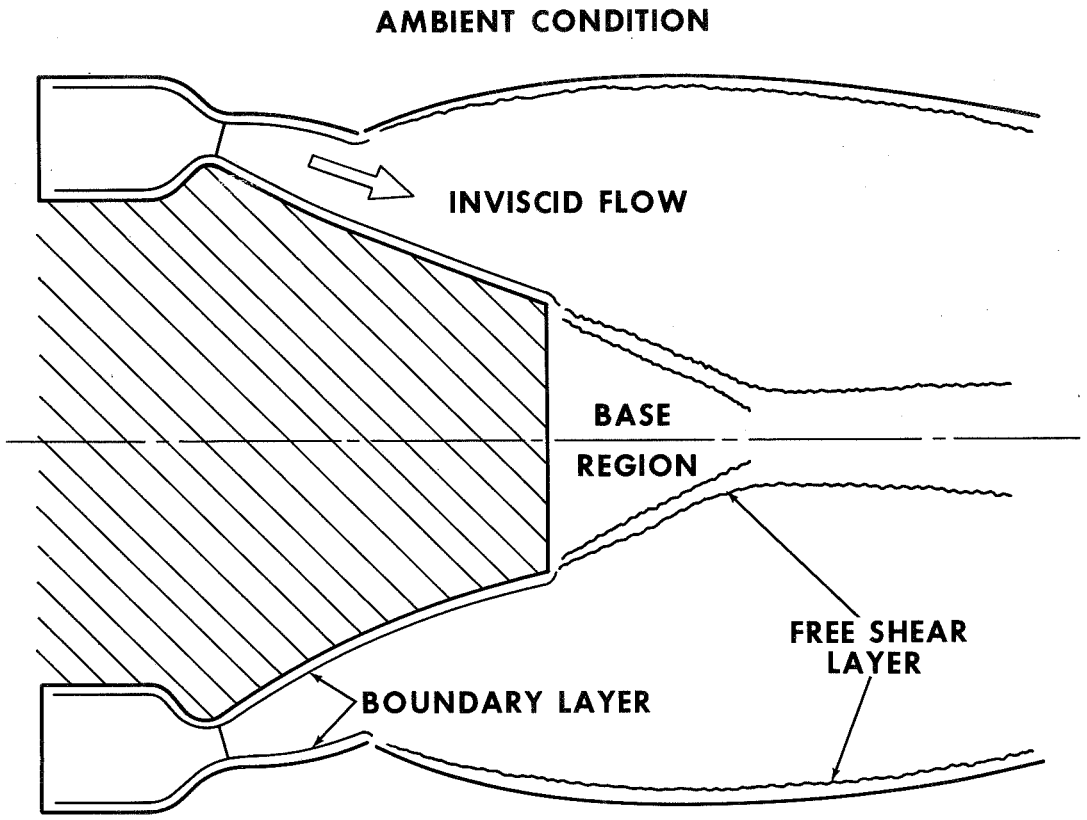


Figure 3. Analytical flow field treatment.

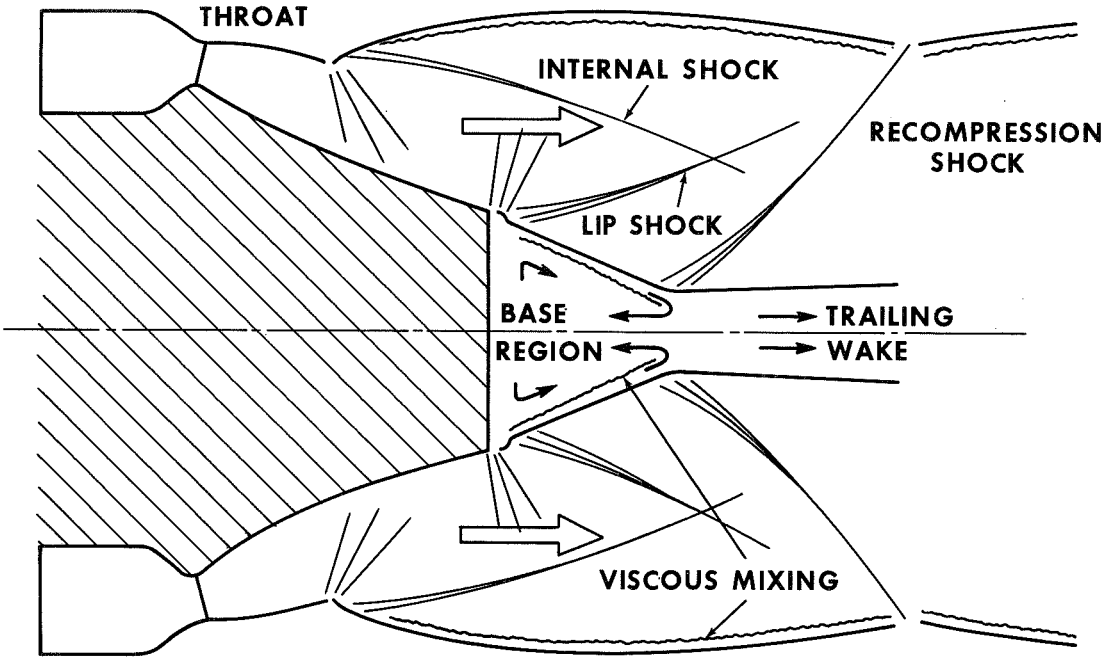


Figure 4. Plug nozzle flow field (closed wake).

open-wake flow the base pressure is slightly lower than the ambient pressure and is approximately constant across the whole base area. Under a closed-wake condition, the base pressure is determined as discussed in the following (Fig. 5).

Downstream of the plug corner a domain, bordered by the lines R and -R, exists in which the mixing free shear layer develops. Within this domain lies one streamline that separates the base recirculation flow from the remainder of the flow field. From the previous analysis the flow conditions just upstream of the corner at location (1) are known. Now, an assumption of the base pressure P_b is made. This base pressure value is assumed to exist at location (2), since a pressure gradient across the shear layer is very small. With the two known pressures, a Prandtl-Meyer expansion can be performed, resulting in the flow angle θ_{1-2} reflecting a conical surface. This cone serves as a geometrical boundary condition and allows one to proceed with the method of characteristics calculation until the trailing wake radius r_w is reached. Simultaneously, the flow condition at location (3) is specified. At this point the flow outside the recirculation area is turned in an axial direction by an angle θ_{3-4}, which is equal to θ_{1-2}, and this results in the generation of a recompression shock. Application of the method of characteristics simulates this occurrence and leads to the flow condition at location (4). Within the shear layer dynamic energy is lost because of the viscous effects, thereby lowering the total pressure continuously. For the correct base pressure solution, the following criterion must be satisfied: the static pressure at location (4) is equal to the total pressure of the streamline dividing the recirculation base flow from the external flow. This means that all particles within the recirculation flow field have a lower total pressure and cannot flow further downstream but will be recirculated instead. If the criterion at the wake radius location is not satisfied, a new base pressure P_b must be assumed and the calculation must be repeated until convergence is obtained.

At present a theory does not exist that determines the location of the recompression shock. Therefore, an empirical relationship relating the wake radius to the Mach number of the inviscid flow at location (1)

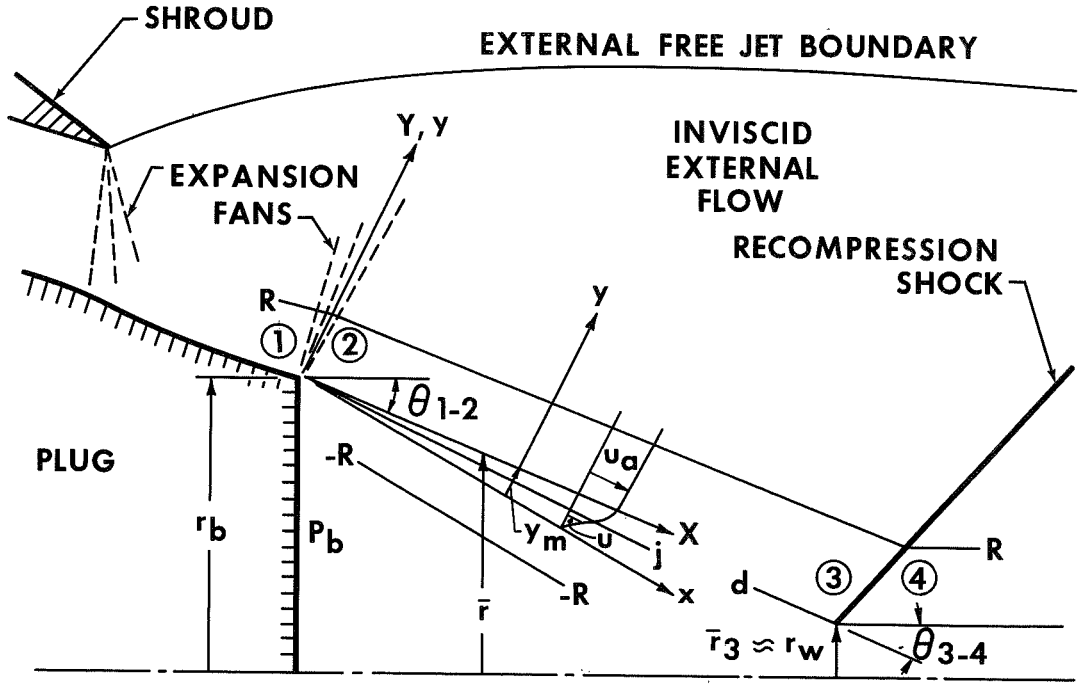


Figure 5. Flow model for the determination of the turbulent base pressure for an axisymmetric plug nozzle.

has been generated (Fig. 6). From this graph a wake radius is obtained for a given approach Mach number, and it is used in the base pressure solution procedure.

It should be mentioned that a base pressure solution for an expansion-deflection nozzle is determined by the same analogy.

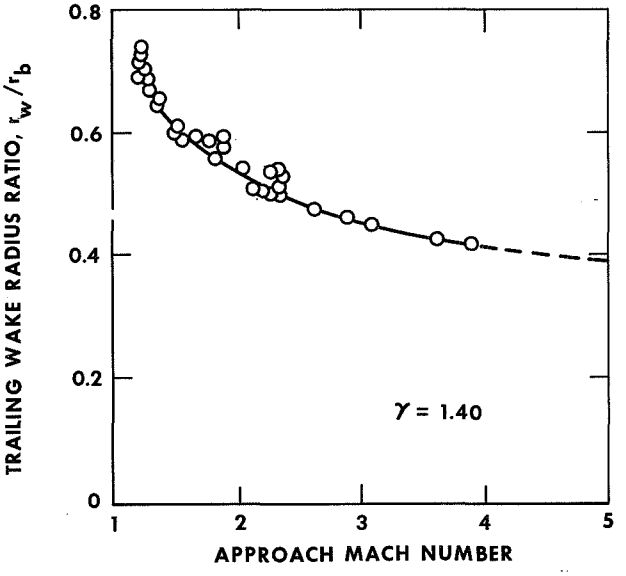


Figure 6. Trailing wake radius ratio versus Mach number for $\gamma = 1.40$

PARAMETERS AFFECTING NOZZLE PERFORMANCE

Sonic Line Shape

For the analytical solution, it is important to know the correct shape and location of the sonic line. Since the method of characteristics solution is based upon a start line slightly greater than Mach number equal to one, it is apparent that the complete supersonic flow field and the nozzle performance is governed by this parameter. Because of the aerospike nozzle geometry, the physical nozzle throat area is not normal to the engine centerline but is inclined by a specific angle. Because of the nozzle contour geometry, the combustion products are accelerated differently such that an axisymmetric sonic line shape, even with regard to the nozzle throat centerline, is not formed. In Figure 7 measurement location, static pressures converted to Mach number, and the interpolated sonic line are presented. To obtain the effect of various sonic line shapes on the base pressure, four different start lines symmetric to the geometric throat were selected. The analytical results presented in Figure 8 indicate that the closed recirculation area and the location of the recompression shock do not change. The base pressure, however, is affected by the start line profile.

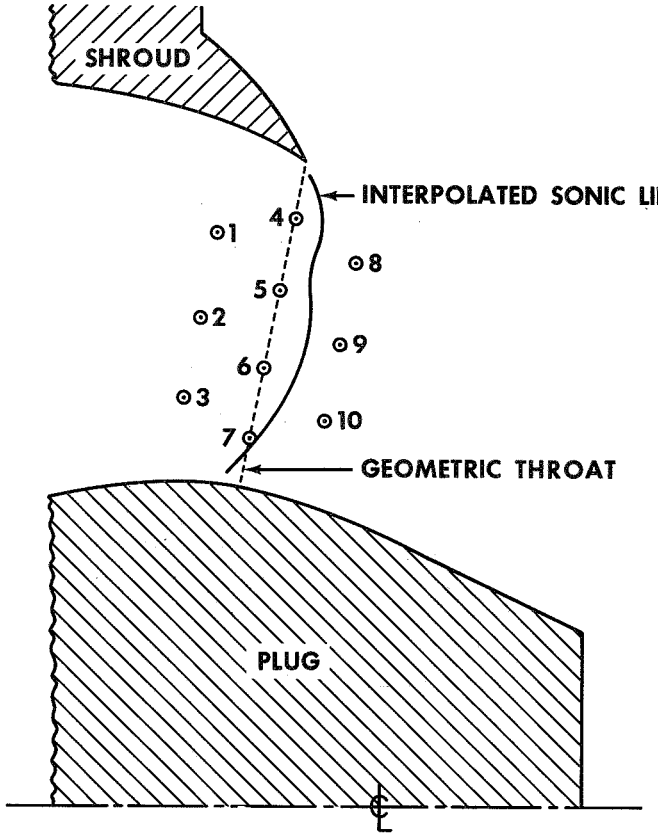
Ambient Pressure

In Figure 9 the flow fields of a planar truncated plug nozzle for various ambient-to-chamber-pressure ratios are presented covering the open- and closed-wake operation mode. The respective base pressure measurements, nondimensionalized by the chamber pressure, are shown in Figure 10 as a function of the external or ambient pressure. During open-wake operation [Figs. 9(a), 9(b), 9(c), and 9(d)], the base pressure follows the ambient pressure very closely. As soon as the closed-wake condition is reached [Figs. 9(e) and 9(f)], the base pressure remains constant.

In contrast to the planar nozzle, Schlieren photographs of an axisymmetric truncated plug nozzle for various ambient pressures are shown in Figure 11 with corresponding base pressure measurements presented in Figure 12. In principle the same characteristics occur in both flow field pictures; however, for the three-dimensional case the characteristics seem to be more pronounced. Here again the base pressure follows the ambient pressure closely [Figs. 11(a) and 11(b)] during the open-wake condition. However, lowering the ambient pressure from the condition shown in Figure 11(b) to that shown in Figure 11(c) generates a sudden increase in the base pressure. This pressure rise is caused by the internal shock emanating from the outer shroud striking the surface of the plug. A further reduction in ambient pressure [Figs. 11(c) and 11(d)] makes the base pressure follow the same trend, however, because of the presence of the internal shock at an elevated pressure level. Finally, when the recirculation wake closes [Figs. 11(e) and 11(f)], the base pressure remains constant.

Base Bleed

Introduction of base bleed flow into the base recirculation area may be used to increase the base pressure and consequently raises the nozzle



PRESSURE TAP	MACH NO.
1	0.66
2	0.72
3	0.81
4	0.88
5	0.90
6	0.91
7	0.99
8	1.18
9	1.10
10	1.12

Figure 7. Location of interpolated sonic line with respect to geometric throat.

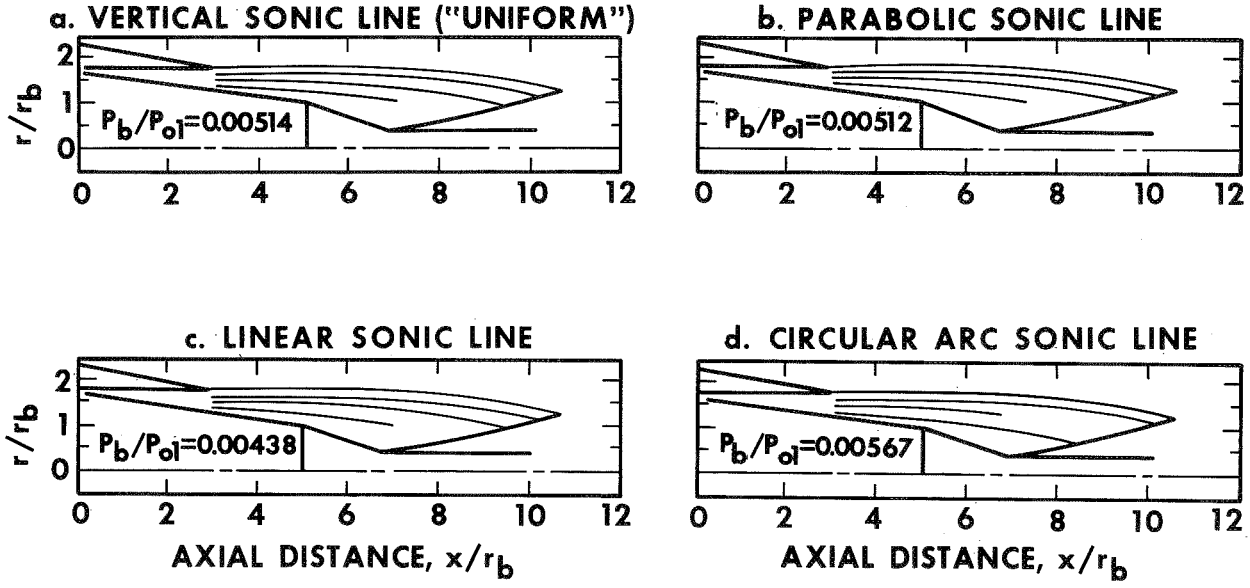


Figure 8. The influence of sonic line shapes for an axisymmetric internal-external-expansion truncated plug nozzle.

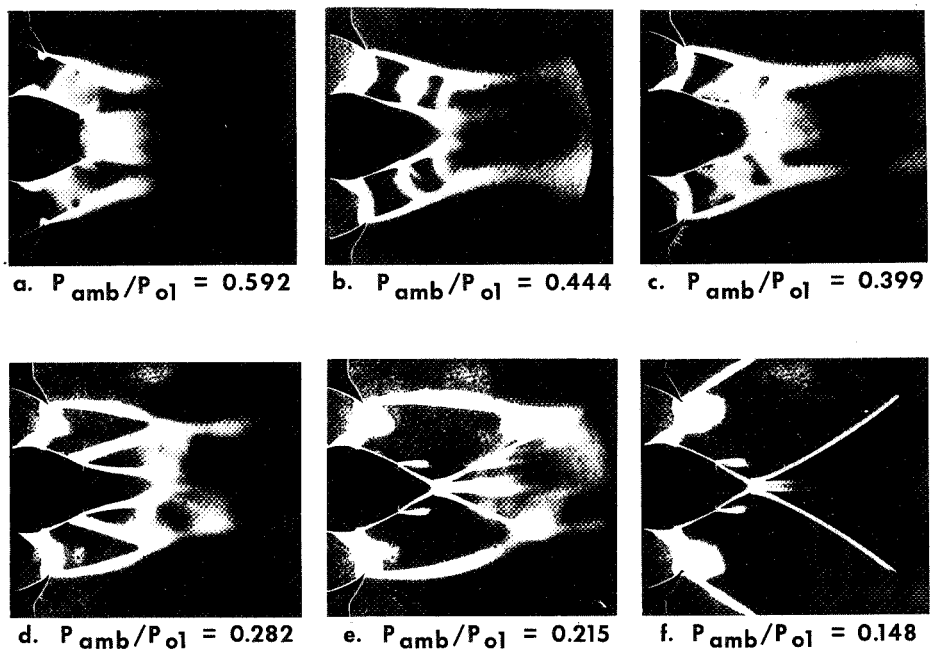


Figure 9. Truncated plug nozzle flow development.

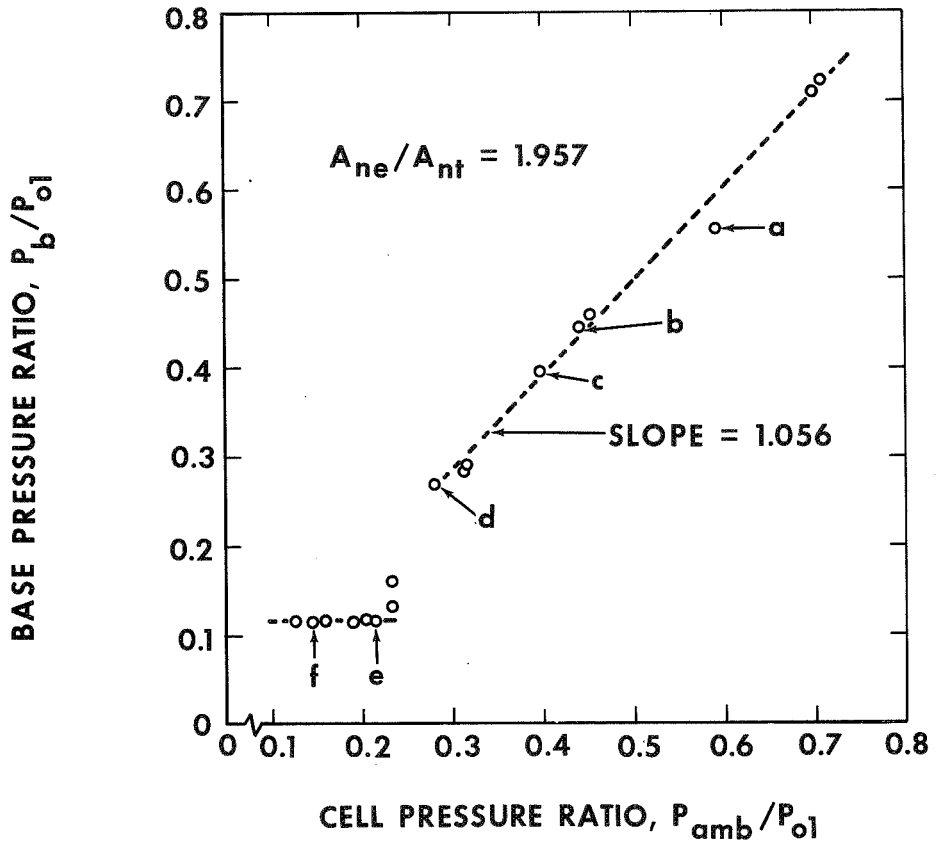


Figure 10. Variation of planar truncated plug nozzle base pressure ratio with ambient pressure ratio.

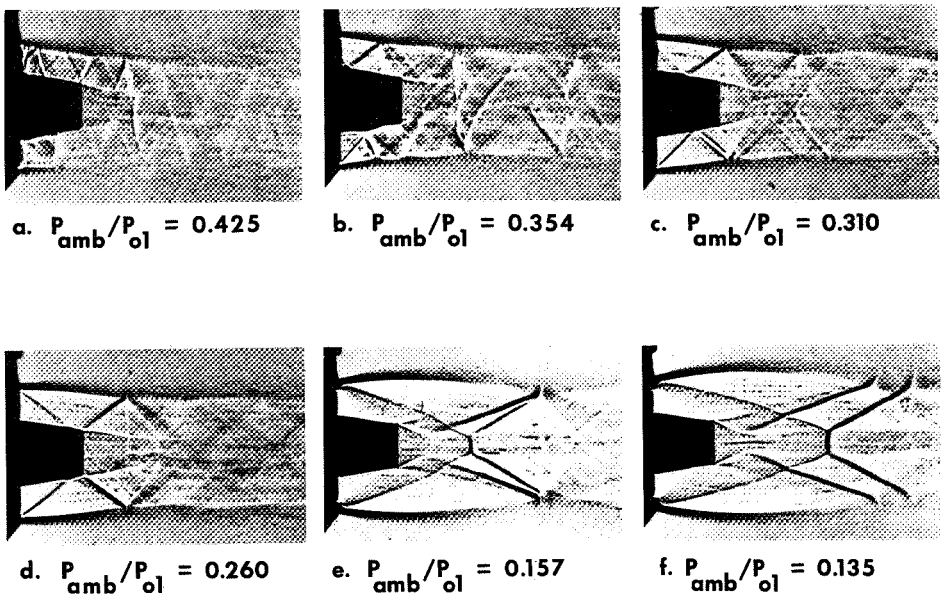


Figure 11. Axisymmetric truncated plug nozzle flow development.

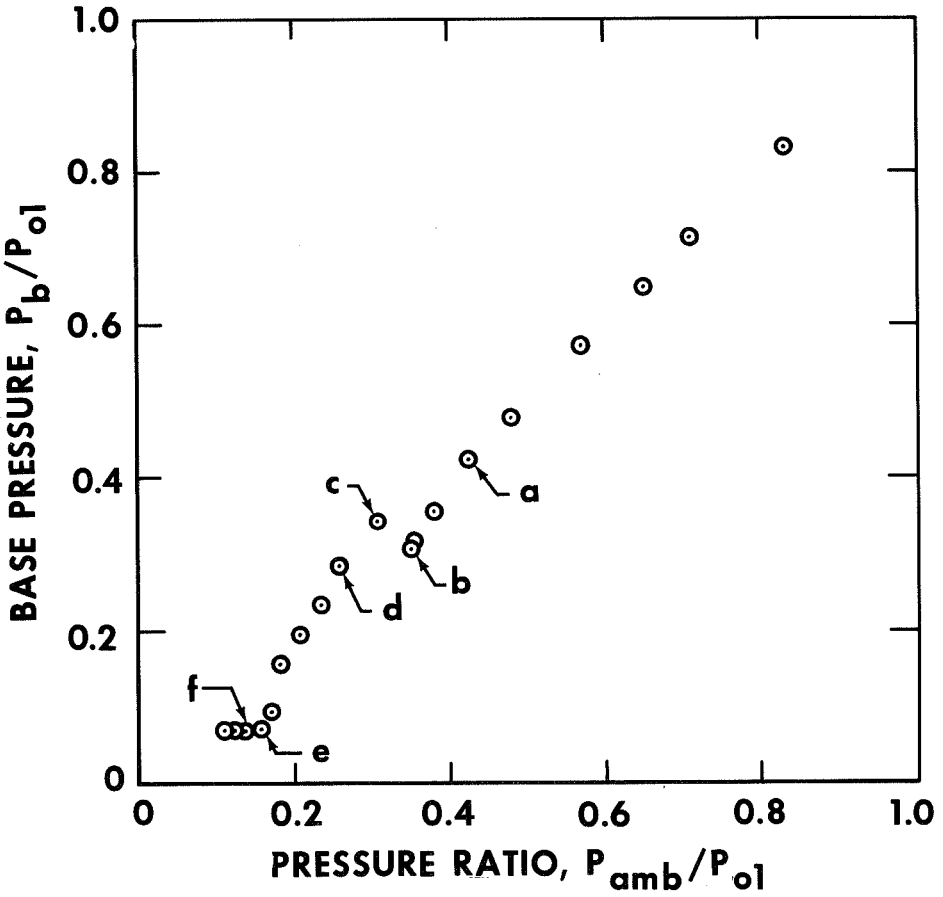
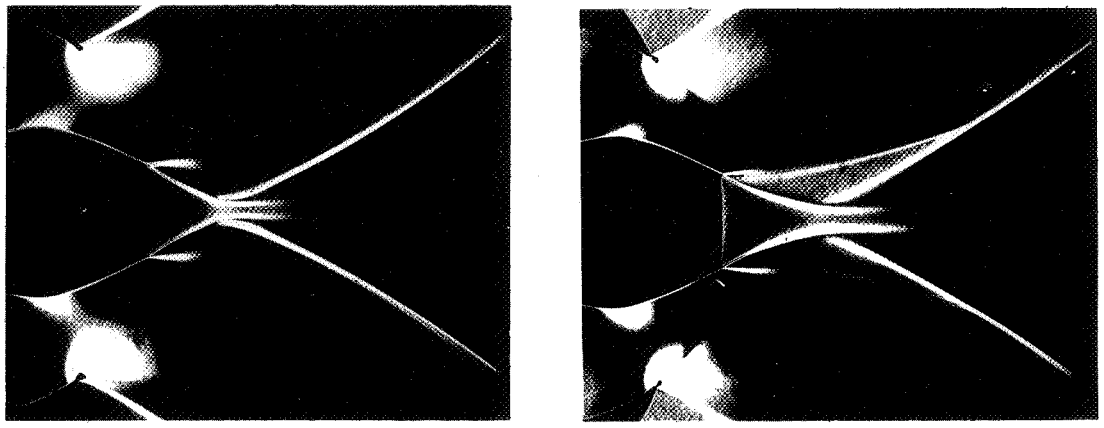


Figure 12. Axisymmetric truncated plug nozzle operating characteristics.

performance. Also, it could be used as a possible means of cooling the plug. Figure 13 shows Schlieren photographs for a test configuration with 0-percent and approximately 1-percent base bleed flow. It is evident from these photographs that even a small bleed rate produces a marked change in the visual flow pattern. The neck of the wake is noticeably thicker and the wake length appears to be longer. Also, the lip shock, which is barely visible in the no-bleed case, has become clearly defined in the flow field with bleed and has changed its position. The effect of base bleed on the nozzle base pressure is presented in Figure 14. As expected, the base pressure increases linearly with base bleed. At approximately 1-percent base bleed with regard to the total flow, a base pressure ratio increase of 30 percent is possible. For base bleed flow greater than 1 percent, the base pressure rise becomes very small and the concept loses its effectiveness. In case of performance optimization, a base bleed flow



a. NO BASE BLEED

b. BASE BLEED 0.82% OF NOZZLE FLOW

Figure 13. Schlieren photographs of planar truncated plug nozzle.

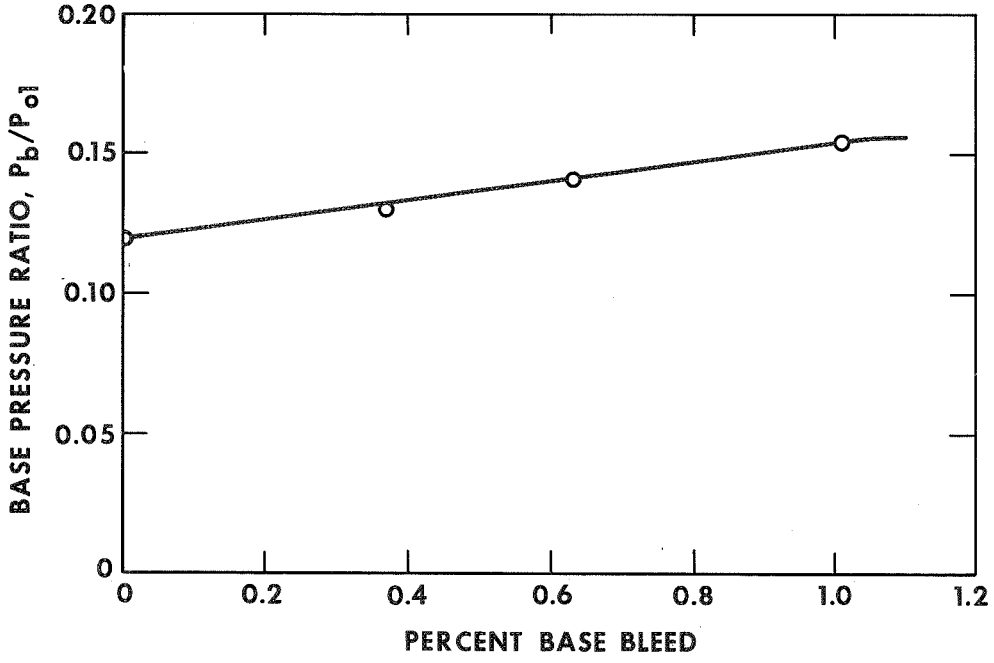


Figure 14. Effect of base bleed on base pressure of truncated plug nozzle.

must be selected such that divergence of this flow from the main chamber flow does not deteriorate the chamber performance significantly, and although the base pressure has been increased, the overall performance is lower.

Nozzle Area Ratio

Increasing the velocity of the combustion products and, therefore, the thrust is possible by varying the overall area ratio A_{ne}/A_{nt} of the nozzle. Results of an analytical investigation are exhibited in Figure 15. Note that an increasing area ratio produces a corresponding decrease in the base pressure. This result is to be expected, since an increasing overall area ratio implies a higher design Mach number of a nozzle.

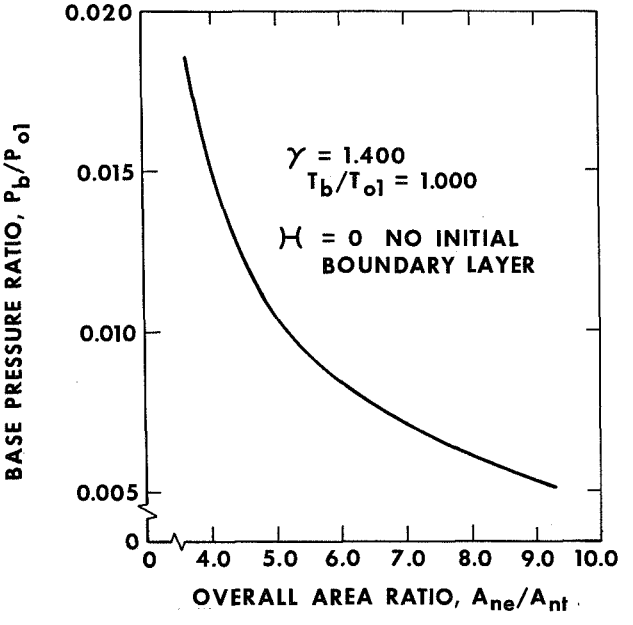


Figure 15. Influence of area ratio on the base pressure ratio of an axisymmetric internal-external-expansion truncated plug nozzle.

Turbulence Effects

Laminar or turbulent flow, especially in the boundary layer, significantly affects the location of the flow where transition from a subsonic to a supersonic condition occurs. The nozzle test configuration, as analytically designed, indicated λ shocks upstream of the geometric throat. Boundary layer trips installed in the subsonic flow area reduced the sequence of λ shocks to a single strong shock which appeared as a slightly curved normal shock. This observation revealed that under normal operating conditions, the boundary layer was laminar and that with the trip, the boundary layer became turbulent. Translating the plug physically downstream by a small amount eliminated the shock formation in the nozzle convergent area. At the same time the effects of turbulence on the nozzle centerline static pressure distribution and the base pressure were investigated. In addition to the boundary layer trip a 0.64-cm (0.25-in.) wire mesh was installed at the inlet to the nozzle section to induce turbulence in the entire flow field. The resulting measurements are shown in Figure 16. The largest deviation in the base recirculation area [from 0 to 2.54 cm (0 to 1.0 in.) distance from the plug base] occurred with the wire mesh and was on the order of 8 percent. The boundary layer trip does not appear to have affected the static pressure distribution in this area. Variation in the base pressure demonstrated the same trends.

Plug Length

In general it is desirable to have as high a closed-wake base pressure as possible to obtain the maximum thrust. Experimental results obtained for the same nozzle configuration with varying plug lengths (Figs. 17 and 18) imply that the most desirable configuration would be that with the plug ending at the shroud exit. This geometry also has the obvious advantages of less weight and a shorter length. However, since the thrust contribution resulting from the base pressure is usually not the major part of the total thrust, other considerations are also important. With a plug extending beyond the shroud exit, the additional plug surface may gather enough thrust to offset both the decrease in base pressure and the increase in weight. Although the base pressure tends to increase for plug lengths greater than $L/L_{max} \approx 0.5$, this extreme of plug length is not practical. As L/L_{max} approaches 1.0, both the plug base area and the increase in plug surface area become very small and the changes in total thrust resulting from pressure forces on these surfaces become negligible.

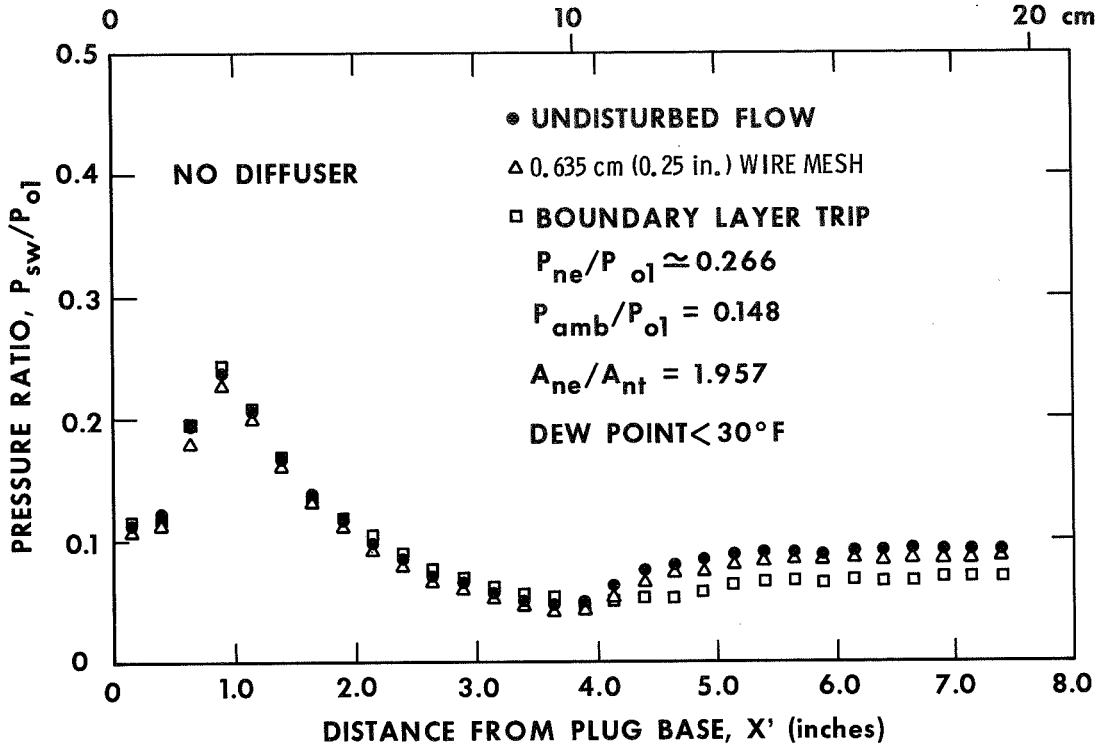
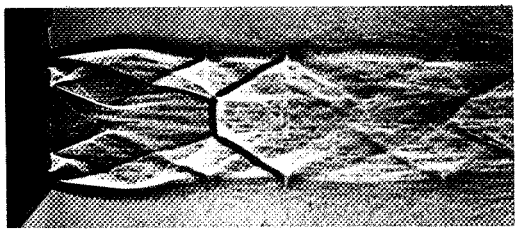
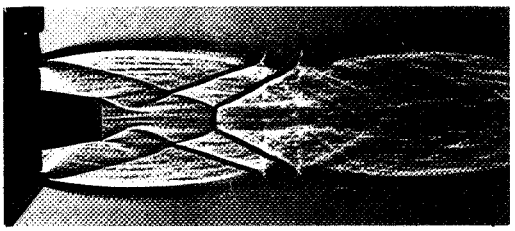


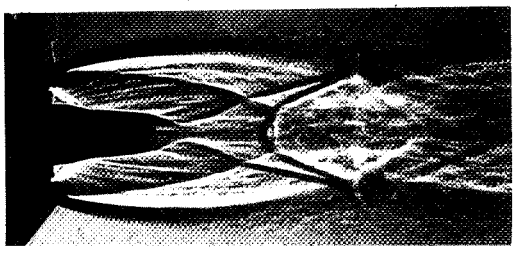
Figure 16. Induced turbulence effects on side-wall centerline static pressure variation of planar truncated plug nozzle.



a. $P_{amb}/P_{o1} = 0.135; L/L_{max} = 0.218$



b. $P_{amb}/P_{o1} = 0.135; L/L_{max} = 0.481$



c. $P_{amb}/P_{o1} = 0.104; L/L_{max} = 0.641$

Figure 17. Nozzle flow fields for three different plug lengths.

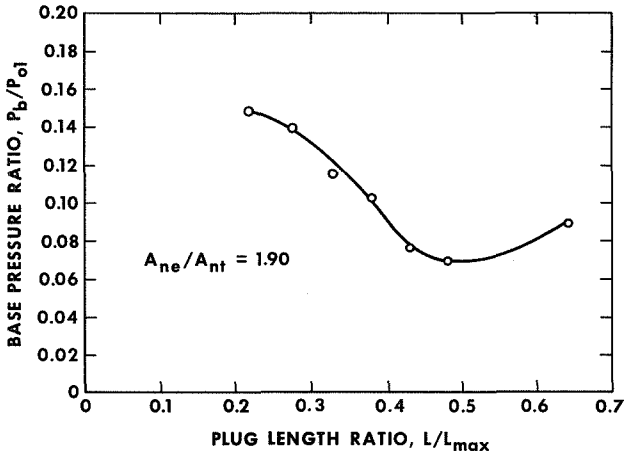


Figure 18. Effect of plug length ratio on the closed-wake base pressure for axisymmetric truncated plug nozzle.

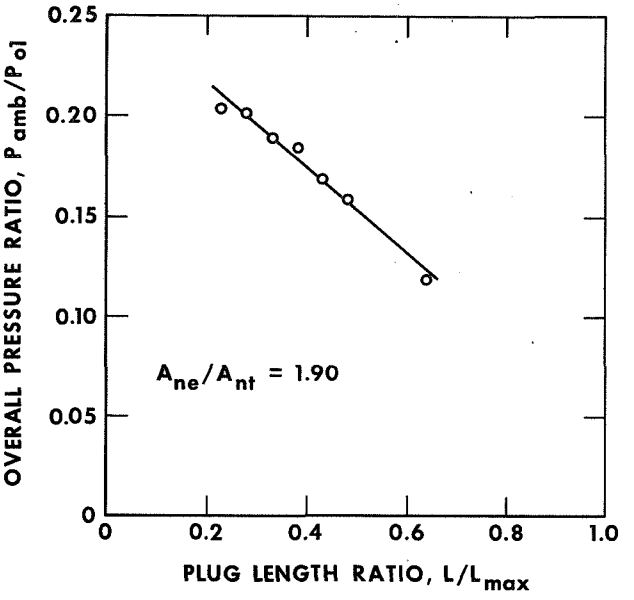


Figure 19. Effect of plug length ratio on overall pressure ratio at wake closure for axisymmetric truncated plug nozzle.

The overall pressure ratio at which the wake closes is important for determining optimum nozzle efficiency. Figure 19 presents this relationship. The increase in overall pressure ratio at wake closure as the plug length ratio is decreased presents further justification for the desirability of shorter plugs. The calculation of total performance for a given mission is greatly facilitated if the base pressure is constant (closed wake) for the longest period possible. Figure 19 indicates that shorter plug lengths lead to the establishment of closed-wake operation at higher values of ambient pressure, i.e., lower altitudes, and therefore increase the percentage of vehicle flying time at the closed-wake condition.

Experimental-Analytical Flow Field Comparison

A flow field Schlieren photograph of an axisymmetric truncated plug nozzle is shown in Figure 20. For performance determination, the subsonic and transonic flow field is of vital importance. However, in the supersonic area, only the flow field bounded by the shroud surface, plug surface, free jet boundary, separated base flow region down to the location of the recompression shock location, and the recompression shock itself is significant.

A comparison between the observed free jet boundary and internal shock location with analytical predictions is presented in Figures 21 and 22. The predicted constant pressure boundary deviates slightly from the observed location downstream of the outer shroud; this deviation was caused by the assumption of flow overexpansion around the shroud lip. In the case of the internal shock location, again a small difference occurs that results from the flow overexpansion assumption and also from the selected shape of the start line governing the supersonic flow field calculation. More accurate input data for the analytical concepts would eliminate these differences.

In Figure 23 the analytical results are superimposed on the Schlieren photograph. In addition to the previously mentioned parameters, the base recirculation area shape, the trailing wake shape, and the recompression shock shape are shown, and they agree well with the observed highly complicated flow field.

Aerodynamic Slipstream

The Chrysler Corporation, Space Division, recently investigated the performance of an aerospike engine in a feasibility study of a single-stage, earth-orbital, reusable vehicle (SERV). The engine is integrated into the base area of the cone-shaped vehicle (Fig. 24). Because of the enormous base area of the aerospike engine, which contributes greatly to the overall propulsion, the performance

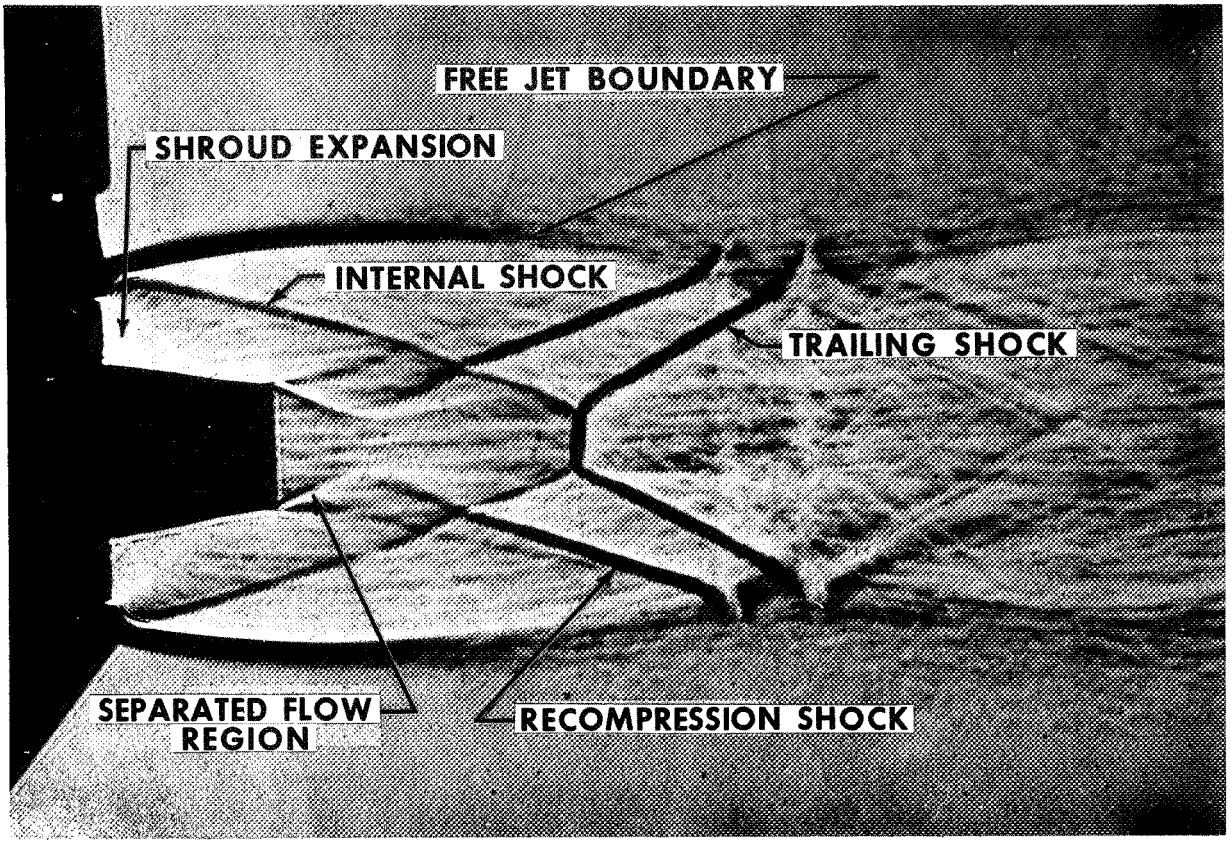


Figure 20. Flow field of the axisymmetric internal-external-expansion nozzle.

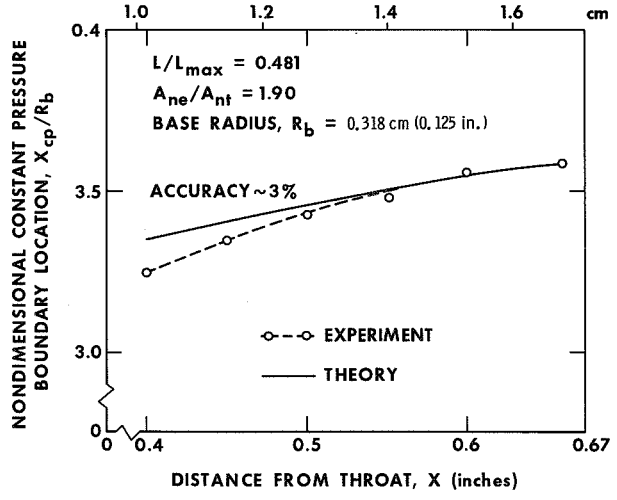


Figure 21. Comparison between analytical and observed constant pressure boundary location for axisymmetric truncated plug nozzle.

during open-wake operation and the condition of wake closure was important. When the vehicle flies through the atmosphere, the body geometry produces a slipstream with conditions in the aerospike engine area that are different from the undisturbed environment. The free jet boundary formed between the nozzle exhaust flow and the ambient air will adapt to the local condition and therefore affect the inviscid nozzle flow field, the base recirculation area, and the base pressure. Since most aerospike nozzle testing has been performed in still air, a wind tunnel test program with a 2.5-percent scaled SERV model using air flowing through the engine was executed to investigate the slipstream or Mach number effect on performance. The results of the test data, modified by scaling laws to account for the full size geometry and hot engine firing, are presented in a so-called carpet plot in Figure 25. This carpet plot does not show any numbers on the abscissa and has been generated by using equal intervals between each 3048-m (10 000-ft) interval for the zero Mach number condition. Such a plot is very convenient for data

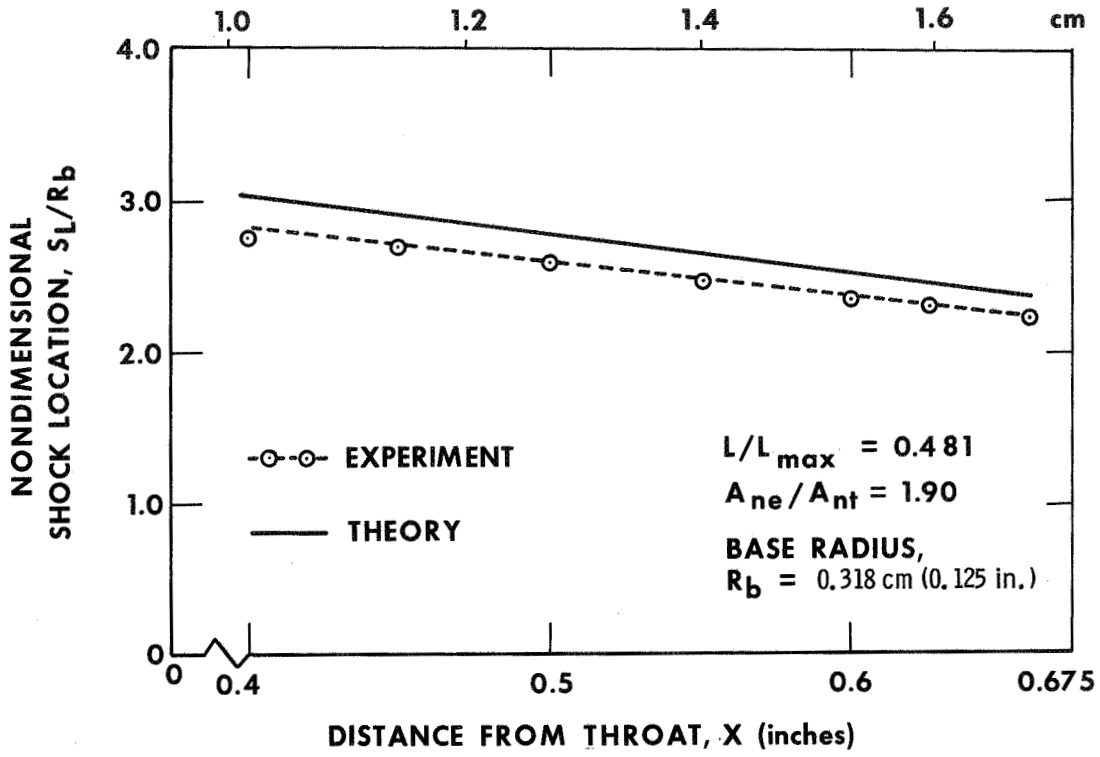


Figure 22. Comparison between analytical and observed internal shock location for axisymmetric truncated plug nozzle.

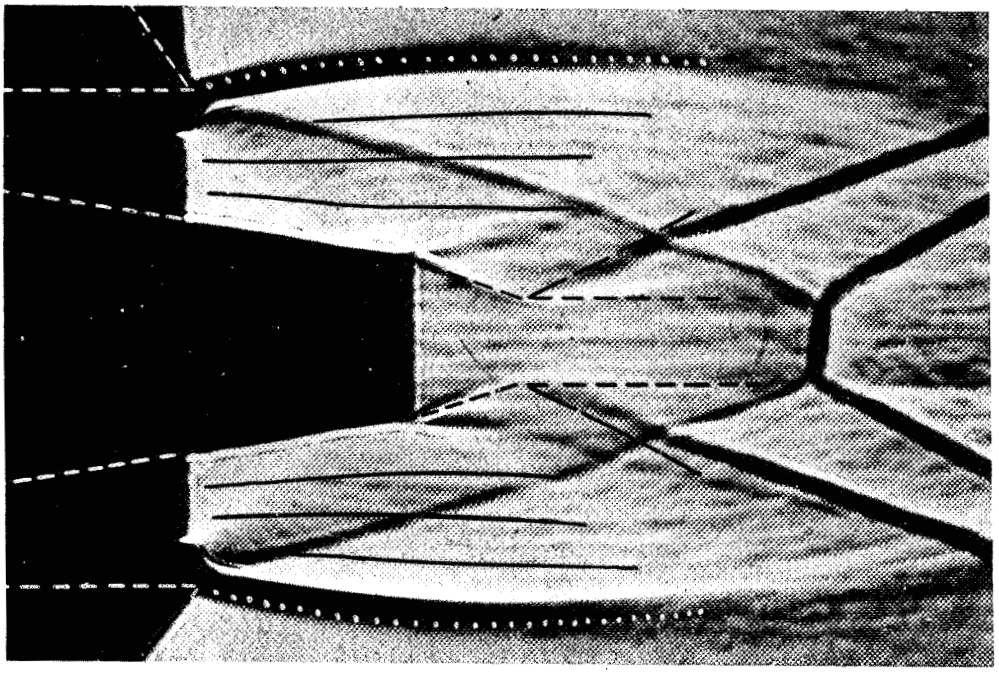


Figure 23. Experimental and analytical comparison of the flow fields of an axisymmetric internal-external-expansion nozzle.

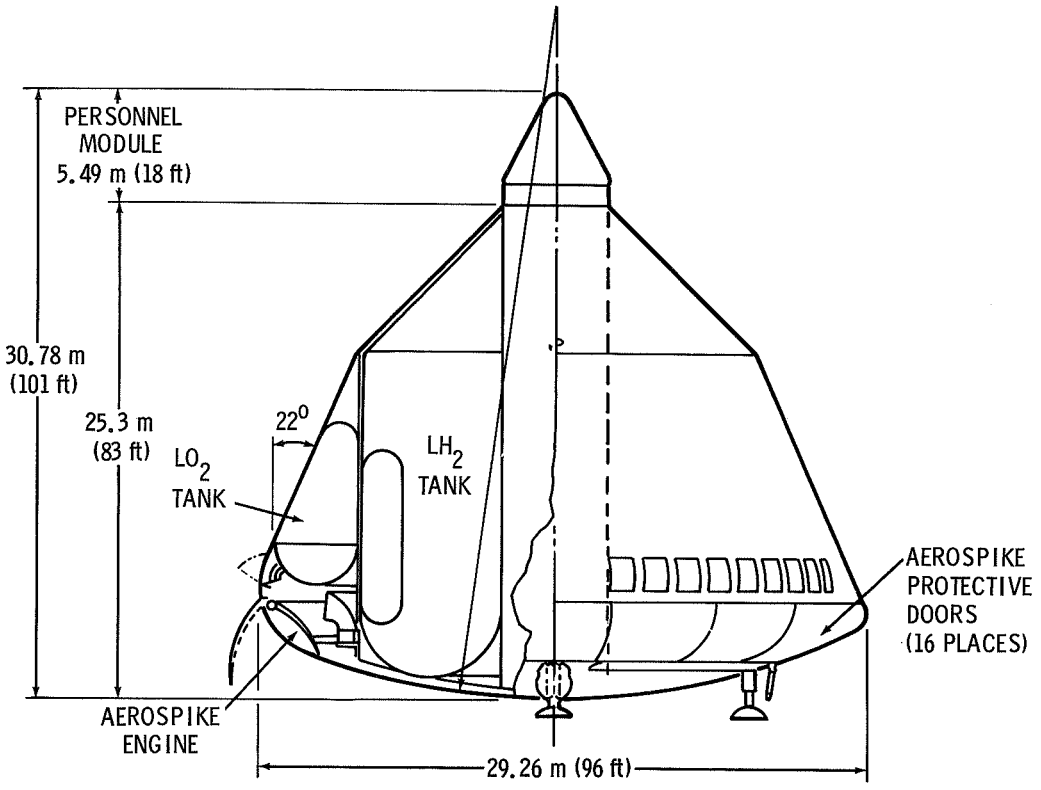


Figure 24. SERV vehicle.

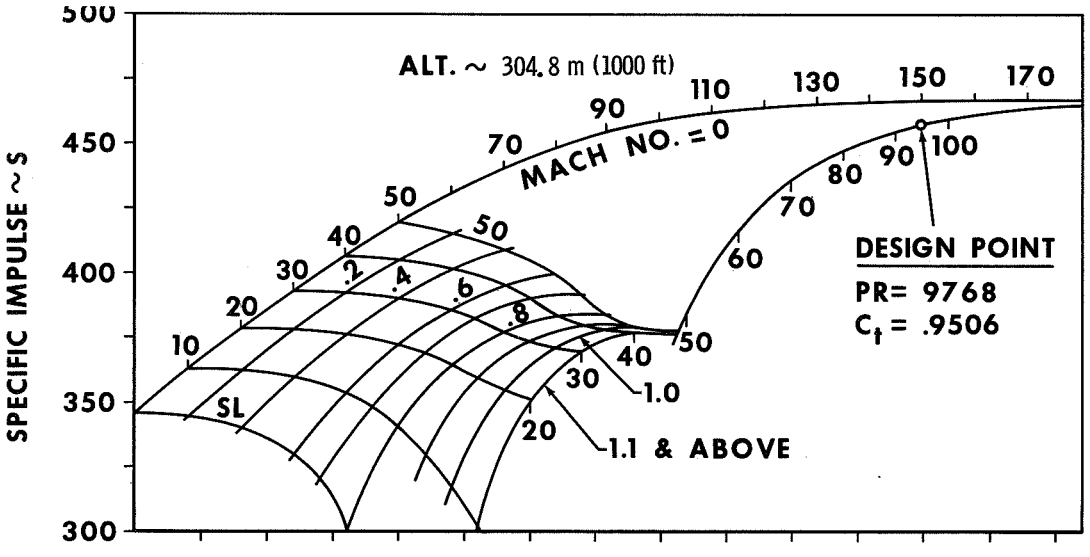


Figure 25. SERV nominal performance of design-point engine ($\epsilon = 433.7$).

interpolation. It is interesting to observe that this engine operates at the point of wake closure with a specific impulse approximately 50 s lower than it would provide in still air. This great difference, however, is caused by the slipstream effect in connection with the tremendous base area.

CONCLUSIONS

An analytical method to determine the performance of an aerospike nozzle, especially the performance contribution from the base area, has been discussed.

Two different types of operation mode exist. The base pressure follows the ambient state just outside the free jet boundary very closely during the open-wake operation mode, whereas the base pressure remains constant for the closed-wake condition. Several parameters such as the sonic line shape, internal shock, ambient pressure, base bleed, nozzle area ratio, turbulence effects, plug length, and aerodynamic slipstream have an effect on the base pressure.

A comparison between experimental and analytical data in connection with visual flow field observance shows good agreement. The parametric presentation of data allows the determination of individual effects and provides a useful tool for aerospike engine performance prediction and optimization.

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